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APPLICATION OF BIODYNAMIC MODELS TO THE ANALYSIS OF F-16 CANOPY--ETC(U)
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The bird impact problem has become especially critical for the new generation of aircraft canopies such as the monolithic windshield/canopy of the F-16. It was required that the canopy be capable of withstanding the impact of a four-pound bird while the aircraft is flying at 350 KEAS. Canopy failure modes identified by testing were fragmentation, penetration and deflection of the canopy material. Of special concern to the Aerospace Medical Research Laboratory were the significant deflections observed as a traveling wave in the canopy material. Biomedical design and evaluation criteria have not been available to apply to this problem. In order to evaluate the degree of crew protection provided by various canopy designs, a (Continued)

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300 College Park Ave.
Dayton, Ohio 45469

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Thirty-eight birdstrike tests were completed by the USAF during the period of March-August 1977. High speed film data were analyzed from the F-16 birdstrike test program to quantitatively define the deflection motion as a function of the initial test conditions. Crewmember position studies indicated probable head contact with the canopy surface during birdstrike at comfortable seating positions. Helmet size and crewmember size were shown to have a negligible effect on increasing clearance between helmet and canopy. A specially instrumented head-neck apparatus was designed and used in the test program to measure the accelerations of the head and the impact forces and moments at the head and neck. The acceleration data from the head-neck test apparatus were used as input to a head injury severity prediction model to determine the level of injury sustained by the pilot. The force data were compared to known injury force levels. A second approach involved the use of the photometric data to describe the response shape and velocity of the canopy and inertial properties associated with the impact as a driving input to a computer model of the helmeted crewman to further evaluate the crewman response to birdstrike.

APPLICATION OF BIODYNAMIC MODELS TO THE ANALYSIS OF F-16 CANOPY BIRDSTRIKE

Lawrence J. Specker*
Norman S. Phillips**
James W. Brinkley*

*Aerospace Medical Research Laboratory
Aerospace Medical Division
Air Force Systems Division
Wright-Patterson Air Force Base, Ohio 45433

**University of Dayton Research Institute
300 College Park Avenue
Dayton, Ohio 45469

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INTRODUCTION

Operational statistics compiled during the period of 1963 through 1972 indicate that a total of 3,548 bird/aircraft impacts were recorded by the USAF. Four hundred and fifteen of these incidents (11.7%) involved impact of the windshield/canopy area of the aircraft. Bird impact occurring in the windshield/canopy area of the F/FB-111 aircraft has resulted in the loss of five of the six US aircraft lost due to birdstrike. One Australian F-111 aircraft has been lost due to a bird impact on the windshield/canopy area. These statistics have been of considerable concern to the USAF and action has been taken to increase the degree of crew protection provided by the windshield/canopy materials. Although the initial efforts have been focused on the F/FB-111 problem, the research has more recently been broadened to study other aircraft systems where unique impact problems might exist.

The latest production USAF aircraft, the F-16, uses an integrated windshield/canopy constructed of a monolithic, polycarbonate material which eliminates the need for the conventional metal windshield frame and thereby increases the visual field of the pilot. To provide birdstrike protection, the canopy is designed to plastically deform to absorb the impact energy. Unfortunately, under certain conditions the bird impact may be severe enough to cause the canopy materials to deform into the space occupied by the pilot. The resulting impact between the canopy and the pilot may cause serious or even fatal injury. Therefore, the goal of the F-16 canopy development program has been to provide a canopy capable of withstanding the impact of a 1.8 kg bird and protecting the pilot from canopy impact while the aircraft is flying at a velocity of 350 KEAS.

Biomedical design and evaluation criteria have not been available to apply to this unique problem. The Aerospace Medical Research Laboratory (AMRL) of the USAF was asked to provide the F-16 Systems Program Office with criteria by which the birdstrike resistance of the canopy could be assessed. The ultimate objective of the research effort has been to provide aeromedical design criteria that can be generally applied during the development and evaluation of new aircraft canopy designs for both current and future aircraft. However, the emphasis of this paper is on the effort that has been accomplished within the cost and schedule constraints of the F-16 canopy development program.

It was clear that proven measuring techniques and established biodynamic models had to be used to remain within the F-16 program constraints. Furthermore, the injury criteria had to be comprehensive enough to describe levels of injury ranging from short period disruption of the pilot psychomotor performance capability to frank major injury such as skull fracture.

Initial efforts were devoted to an investigation of available bird impact testing techniques. Test methods used to impact aircraft canopies were reviewed with the primary emphasis placed on evaluation of existing measurement techniques, description of their limitations and the potential for their improvement. Measurement of the canopy response was found to be best accomplished by use of high-speed motion picture photography although the accuracy of this technique left much to be desired.

Measurement of the response of the impacted crewmember was a major problem. The initial experimental efforts accomplished by airframe contractors utilized anthropometric dummies or specially instrumented headforms. The data collected from tests with the anthropometric dummies were of little value since the dynamic response properties of the dummies were unknown and the instrumentation within the dummies was very limited. The special headform devices were similarly unacceptable since these devices contained elastic structural elements of unknown dynamic response characteristics and the instrumentation had also been limited. Furthermore, the headform device could not simulate the interaction between the head-neck system and the torso dynamics. To partially resolve this problem, a specially instrumented and calibrated headform was designed by AMRL. This device is instrumented with accelerometers to measure the acceleration of the headform. The impact forces and moments reacted through the neck of the head-neck system are measured by an array of six force cells. This device is shown in Figure 1. An approach was still required to determine the interaction between the head, neck and torso. Moreover, an approach was required to analyze existing canopy test data and to provide a design tool to analytically evaluate the influence of factors such as pilot position, helmet thickness, etc.

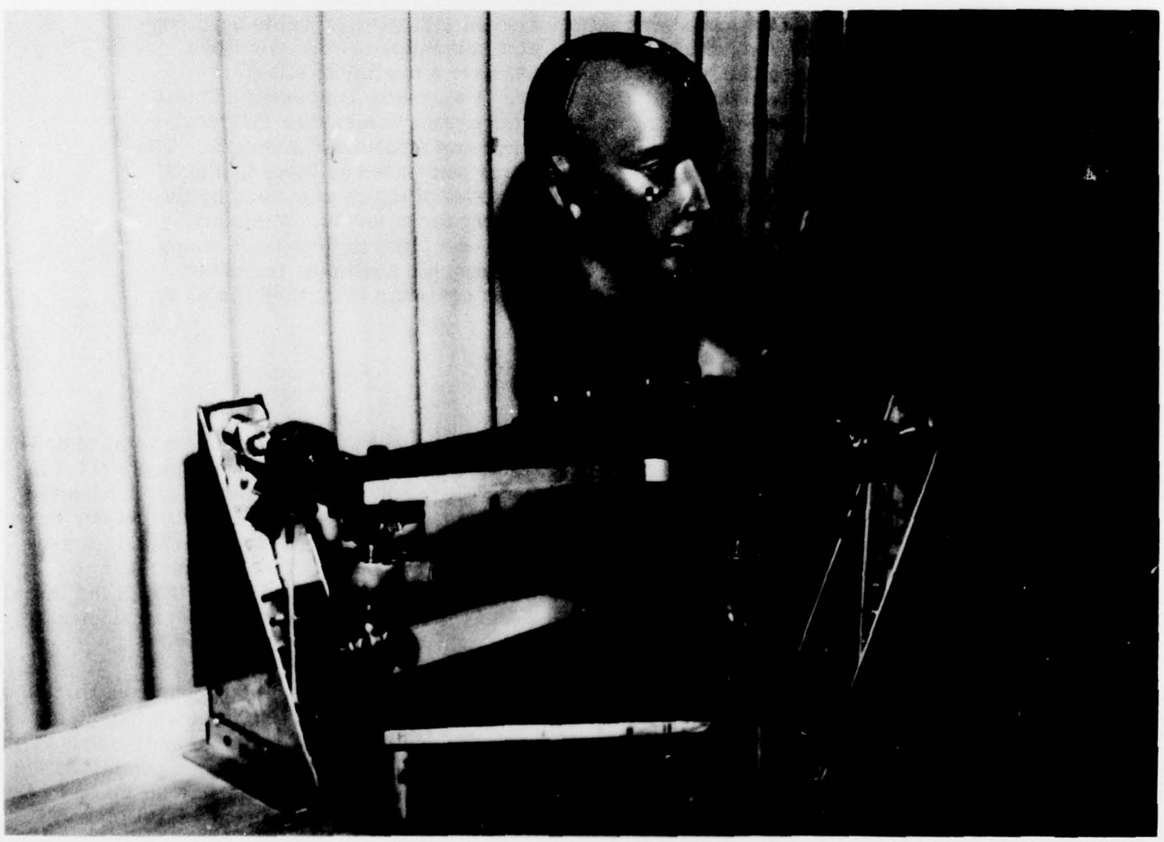

Figure 1. Instrumented Head-Neck Apparatus

In order to establish an analytical procedure to evaluate the effects of the impacting canopy on the crewmember, five candidate approaches were reviewed. These were:

1. Characterization of the aircraft canopy and crewmember in terms of finite element models.

2. Use of a chain model similar to the three dimensional Calspan model to represent the human body. The canopy deformation wave impacting the crewman would be represented as a geometric object.

3. The canopy, the head-neck inertial response characteristics and the injury response of the crewmember would all be represented by lumped parameter models.

4. Acceleration, forces and moments measured by the instrumented headform device would be evaluated using waveform evaluation methods such as the Gadd Severity Index (SI) and the Head Impact Criteria.

5. Measurements made with the instrumented headform device would be compared to available human tolerance data collected under specific test conditions.

Each of the candidates, of course, had specific advantages and disadvantages. The finite element modeling approach was attractive from a long range point of view since the Air Force Flight Dynamics Laboratory was sponsoring a research effort to model the aircraft canopy using this technique. Nevertheless, the approach was complex and human impact response models of this type were nowhere near the point of validation with experimental data and correlation with impact tolerance limits. The chain modeling approach offered many advantages; the most pronounced of these being availability, some validation with human impact experimental results, and the relative ease with which the computer program could be modified to meet the objectives of this program. Its primary disadvantage was that it could not be used to determine if injury limits had been exceeded. The modified three dimensional Calspan model, a chain model used by AMRL, hereafter referred to as the Articulated Total Body Model (ATBM), was available and could be used to predict whole body inertial and kinematic responses.

Lumped parameter modeling approaches were approached with caution. From the standpoint of biomedical applications, they are often oversimplifications of human body subsystems and injury responses. Nevertheless, the lumped parameter model referred to as the Maximum Strain Criteria (MSC) head injury model developed by Stalnaker was available and had several especially attractive features. First, relatively large amounts of human and animal experimental data had been used to develop the model parameters. Second, the model could be used to calculate levels of injury which had been correlated with experimental pathology. Additionally, the model had been developed specifically for the study of the effect of direct impact to the head for cases of both frontal and lateral impact.

Waveform evaluation methods were considered initially and had, in fact, been used to analyze some of the early birdstrike data collected during the development of a new F-111 canopy; however, these methods presented extreme limitations in the F-16 application. The most critical limitation was the fact that the available systems such as the Gadd SI method evaluate the effect of the impact in terms of an absolute limit, an SI of 1,000, which is assumed to be related to occurrence of linear skull fracture. The authors are not aware of any attempt to correlate the SI with other levels of injury.

The empirical approach offered no advantages and was included in the study for completeness only.

The selected approach was a combination of several of the candidate approaches. Briefly, the approach included:

1. Use of the ATBM to calculate the dynamic inertial and kinematic response of the human body.

2. Modification of the ATBM to include an analog of the flight helmet which could be used to determine the effect of the helmet shell and liner on the transmission of impact forces to the human head.

3. Analysis of photometric data collected during birdstrike tests to develop impact forcing functions to be used to calculate the response of the ATBM.

4. Use of the ATBM head acceleration-time history to drive the MSC head injury model and thereby determine strain level.

5. Measurement of the forces, moments and accelerations at the center of gravity (CG) of the head and neck using a specially instrumented headform for comparison with the calculated head and neck response of the ATBM.

6. Use of ATBM calculations, validated with the experimental measurements, were then related to injury criteria describing rotational, and translational acceleration and velocity limits and head-neck forces and moment limits.

This approach was the most likely to be able to evaluate the influence of the interrelationships of parameters such as the initial position of the crewman's head, bird size, bird impact velocity, canopy

response characteristics, and helmet liner thickness upon the overall estimate of injury severity. The paths that were followed in pursuit of this technical approach are shown in Figure 2. The highlights of the research efforts that were accomplished are summarized in the following text.

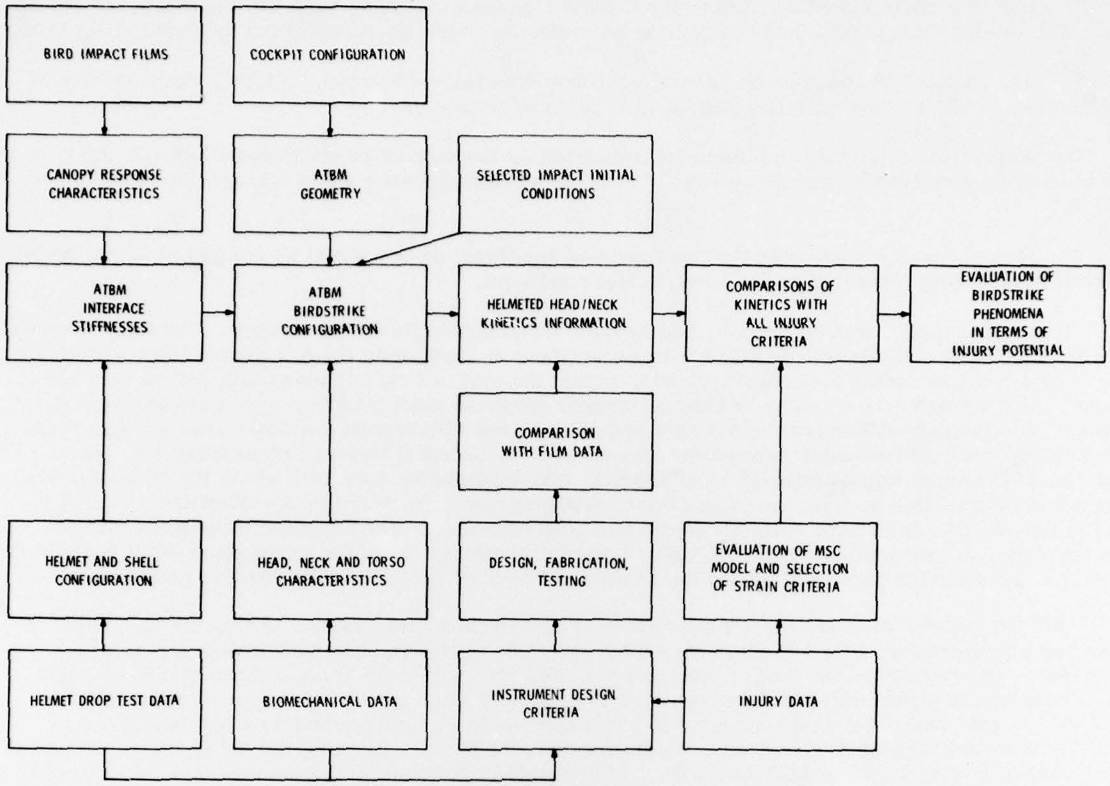

FIGURE 2. FLOW DIAGRAM OF TECHNICAL APPROACH

DESCRIPTION OF CANOPY RESPONSE

The first objective of the analytical effort was the development of the quantitative description of the characteristics of the aircraft canopy at the point of impact with the crewmember's helmet. The parameters necessary for analysis were canopy curvature, velocity and compliance. Data collected during 38 tests conducted for the F-16A alternate canopy design program at the Arnold Engineering Development Center and at the General Dynamics Corporation were made available for analysis. These data consisted of high-speed motion picture films collected during the bird impact tests. The tests were conducted with bird masses of approximately .9, 1.4 and 1.8 kg impacting the canopy at velocities ranging from 123 to 363 knots. Figure 3 shows the F-16 canopy with the head and neck test apparatus in place prior to impact tests.

Figure 3. F-16 Canopy Test Fixture with Head-Neck Apparatus in Place

Using photometric analysis techniques, the value of the maximum canopy deflection was determined and the average wavespeed from the point of maximum deflections to the head location was calculated. The results are plotted in Figures 4 and 5. The displacements that are plotted in Figure 4 are those of the interior of the canopy relative to the original undeformed canopy center line as seen in a side view. The plot of maximum amplitude appears to be bilinear whereas the amplitude of the deformation measured with respect to aircraft station 140.0, the vertical axis on which the design point of the pilot's eye is located, is nearly linear with kinetic energy. The maximum amplitude of the canopy deformation was greater than 12.7 cm at large energy levels for even the thickest canopy that was tested.

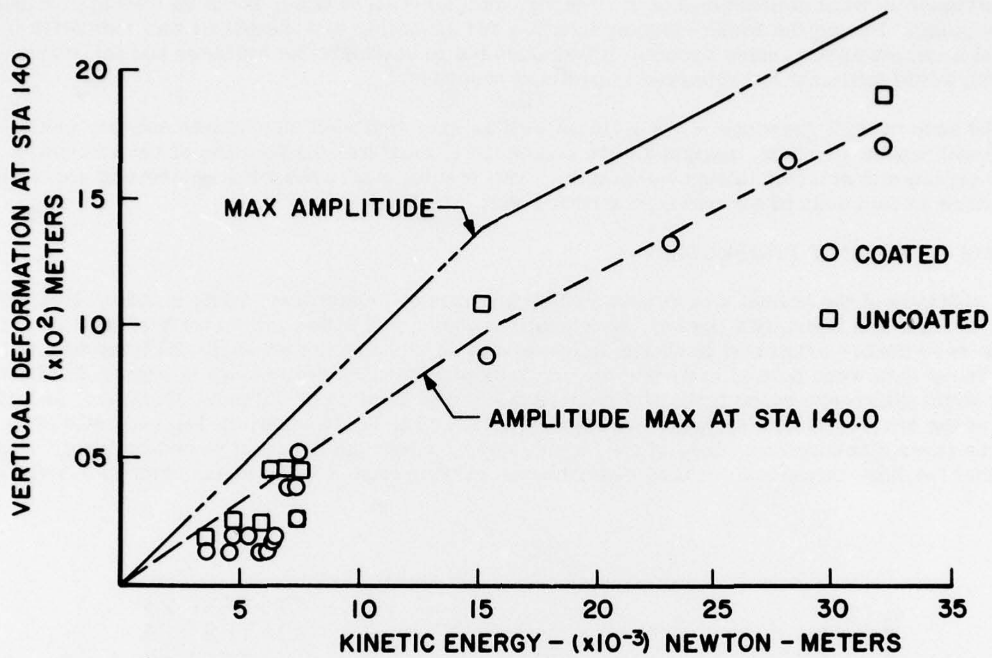

Figure 4. Vertical Deformation at Sta 140.0 vs Kinetic Energy of Bird for 1.27 cm Thickness

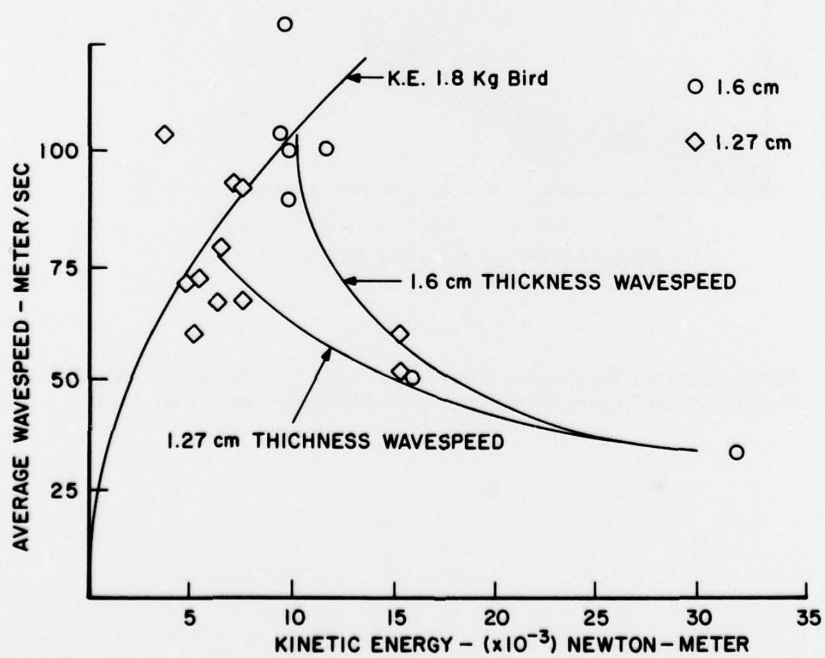

Figure 5. Wavespeed vs K.E.

Figure 5 indicates that the speed of the canopy deformation wave may decrease with increased kinetic energy. This is attributed to the fact that at higher impact velocities the bird is disintegrated in a very short period of time. The impact is, therefore, impulsive in nature and permits the canopy to respond in a free-vibration mode rather than as a forced response as exists at lower impact speeds. At the highest impact speeds, the canopy deformation wave is traveling at less than one-fifth the impact speed of the bird.

A further purpose of the analysis was to determine the compliance of the canopy. Published data collected by impacting birds against instrumented plates provided an approximate means of estimating the peak force and waveform associated with the impact. A study of the motion picture films revealed that the maximum normal deformation of the canopy, as a function of time, could be well approximated by a half-sine pulse. Having the impact forcing function and assuming that the output was indicative of the response of a simple spring-mass system, it was possible to calculate the stiffness and the inertia of a model which would duplicate the observed impact and response.

Based upon cockpit drawings of the F-16 as well as data available on seat adjustment, visual requirements and anthropometric data, analyses were conducted to establish the location of the aircrewman relative to the canopy and selected design eye points. The results were presented in terms of envelopes of helmet volume as functions of aircrewman size and seat location.

DEFINITION OF HELMET PROPERTIES

The stiffness of the helmet was determined by a series of impact tests using standard HGU-22/P helmets with foam and fitting pad liners. Accelerations measured within the metal headform used for these tests were doubly integrated to obtain deformations across the helmet shell and liner as a function of time. These data were plotted to create the force-displacement curves shown in Figure 6. These indicate a slight difference in the form of the curve due to the location of the point of impact, and due to the shape of the anvil on which the headform was impacted. The curve shown in Figure 7 was used to describe the force displacement curve of the helmet liner. From the data that were available, it was assumed that the liner thickness could be described as varying from 2.5 cm at the brow to 3.2 cm at the crown.

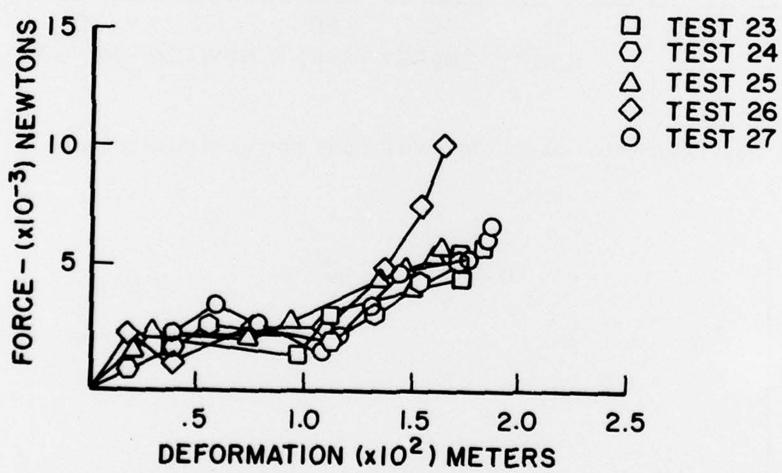

Figure 6. Force Deformation Curves from Drop Tests on HGU-22/P, with Fitting Pads, Helmet Impact Velocity of 3.99 Meter/Sec onto Flat Anvil

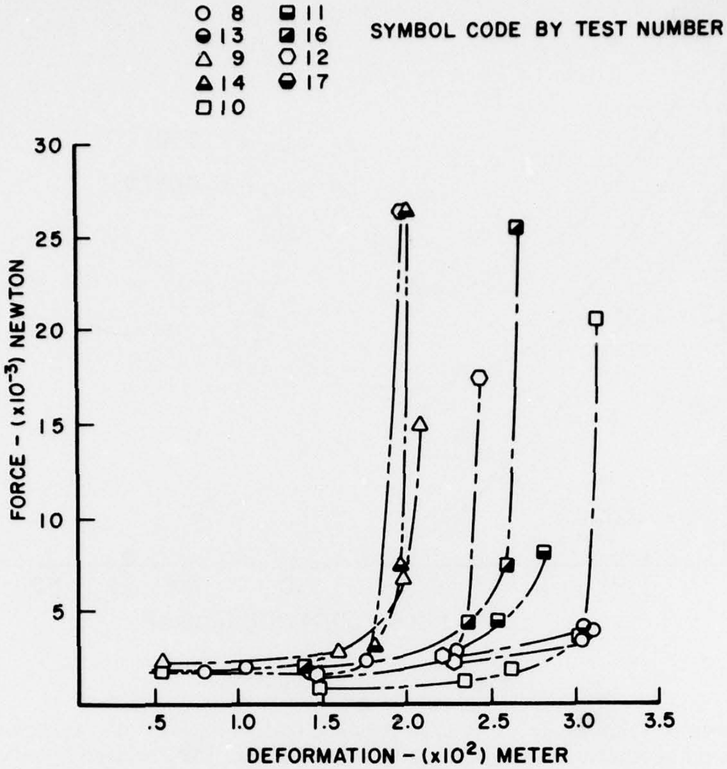

Figure 7. Force Deformation Curves from Drop Test Data on HGU-22/P Styrofoam, Insulite & Foam Helmets Impact Velocities of 4.95 & 5.15 Meter/Sec

HEAD AND NECK CHARACTERISTICS

The ATBM of the human can only duplicate the response of the human body to impact if the proper input coefficients are specified. During the initial phase of the analysis, the ATBM was configured to reflect the response of a 95th percentile anthropometric dummy. As published biomechanical data became available, the coefficients used were compared with those developed to match human responses. The report of Schneider, et al, was particularly applicable since coefficients for an analytical model of the human head and neck had been developed to duplicate the head kinematics of 18 subjects. Furthermore, the coefficients were for a model having similar body segments and joints as the ATBM. The coefficients developed by Schneider were compared with those being used at AMRL and it was found that the differences were negligible. Hence, the values of stiffness and damping for the joints, mass and mass moments of inertia for the segments are in agreement with those known to duplicate observed head and neck response.

INJURY LIMITS AND INJURY MODEL

Many sources of injury criteria were reviewed to establish parameter value limits that could be used in the injury model. Many investigators have published results related to particular parameters such as head acceleration, head velocity change, or head rotational velocities. But selecting the MSC model as a means of evaluating the effect of waveform dictated the need to select a particular strain as a limit. Additionally, strain values were required to be assigned to specific injury scale levels as appropriate to the birdstrike application.

Stalnaker's work was analyzed to determine an acceptable strain level as indicative of concussion. The original strain value of .0061 cm/cm was selected based upon experimental data collected at an injury scale level of 3, "marginal as to whether injury is reversible (i.e., results in permanent disability of function or structure)." This injury level was obviously too severe for the F-16 application. The data were reviewed and the procedure established by Stalnaker was followed to determine a strain level comparable to an injury scale value of 1, "no injury-minor injury." By using the "no injury" data, finding appropriate scaling parameters, and then relating the scale value to strain, a value of .0022 was determined. A plot of constant value strain at .0022 is shown in Figure 8 with the values of .0061 and .00329. It was realized that a strain of .0022 would create extremely severe restrictions on the acceleration environment permitted. The strain level for no injury is too conservative and that for marginal injuries, too severe.

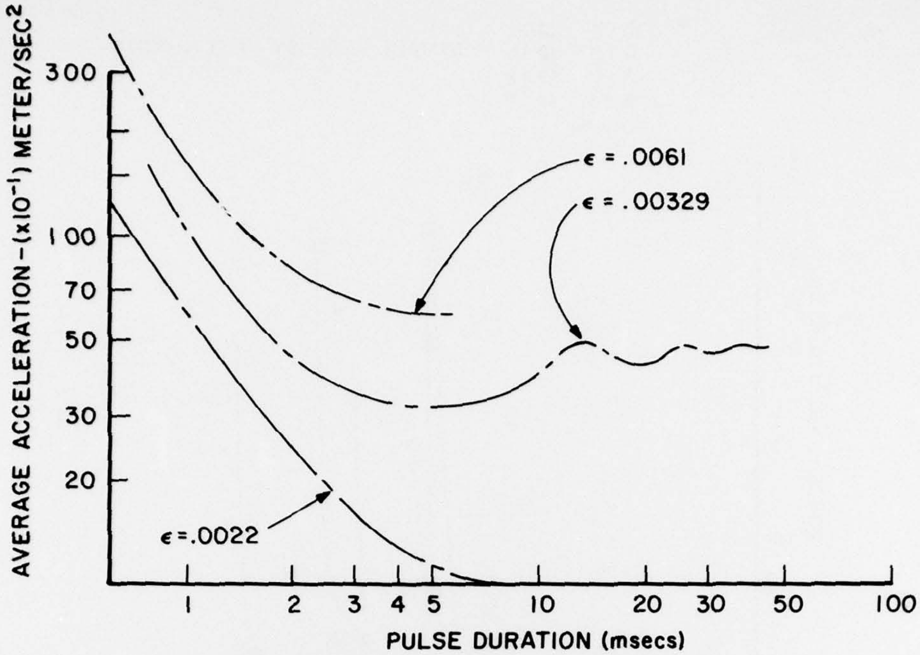

Figure 8. MSC Variations

Data were collected from many sources to relate measured injury to a parameter which could be related to translational acceleration and plotted upon the existing MSC tolerance curves. Data were available from head impact experiments, whole body experiments, and theoretical studies. The criteria for injury ranged from skull fracture to brain shear stress and normal pressure. All results were related to the deceleration pulse which created the "injury" and were plotted on Figure 9. The plotted points indicate that indeed above a strain of .0061, all points were considered "injurious." All points below .0022 are "noninjurious." Consequently, it was necessary to establish some level between the two which could be acceptable. The value selected was .00329 for two reasons. First, the only points of intolerable head response that are below that strain limit are those generated by theoretical models, not experimental data. The points above the limit are points of observed skull fracture. Secondly, the strain value of .00329 was originally established by Stalnaker and McElhaney using the Eiband point (a rectangular pulse of 50 G and 45 milliseconds) as the "survival" acceleration pulse.

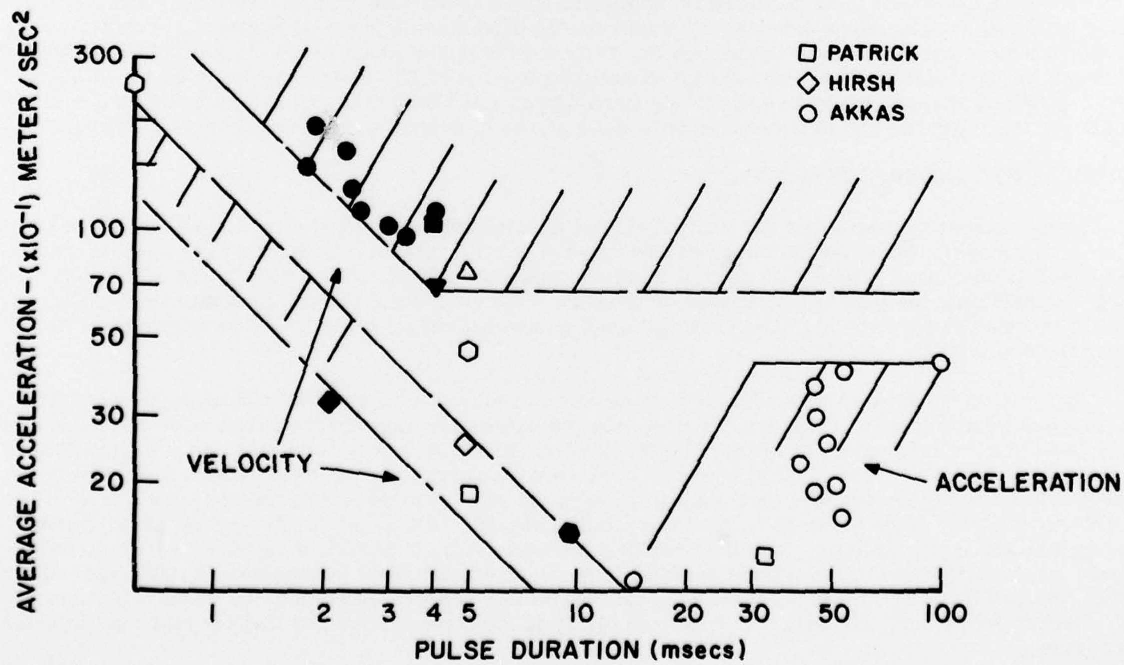

Figure 9. Compilation of Translational Data with Approximate Boundaries for Tolerable Response

The value of strain selected and the models evolved from measured data establish tolerance curves for both longitudinal and lateral head impacts. These are shown in Figure 10. Both assume that injury is related to an idealized strain between "model" elements of skull and brain, and that limiting brain strain is independent of the direction of impact.

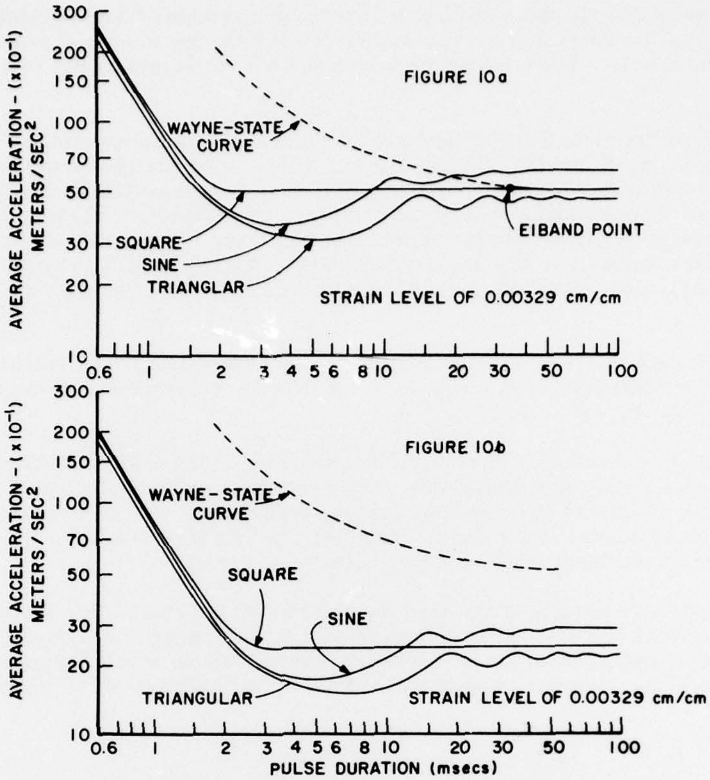

Figure 10. Maximum Strain Criterion Curve for Human Lateral Head Impact

INCORPORATION OF CHARACTERISTICS INTO AN ATBM REPRESENTATION

Use of the ATBM requires that all body sement joints, impact surfaces, and their mutual stiffnesses be defined. The canopy was described as a deformation wave traveling at a given speed and angle to the horizontal. This was duplicated by having the occupant translating forward and the canopy deformation wave moving upward at the time of impact. The location of the deformation wave was established by specifying a particular interference between a nondeforming sphere and helmet shell. Since the shell was of a fixed radius in the sagittal plane, and the direction of the deformation wave was specified, the location of the center of gravity of the deformation wave was established such that the deformation wave and helmet touched at the beginning of each computer run. The maximum interference between the two identifies the computer run being examined.

The stiffness required for analysis was constructed by assuming that the characteristics of deformation wave and shell act in series. The two stiffnesses generate one force-displacement curve which was entered into the computer program. This dictates the kinetic response between the canopy deformation wave and the helmet shell.

The shell was duplicated by an ellipsoid having the curvature of a helmet and separated from the head by a varying liner thickness. The head used had inertial properties indicative of a 95th percentile aircrewman, and had head-neck and neck-torso elasticity and damping coefficients comparable to those developed by Schneider. The torso was that of the 95th percentile individual.

RESULTS OF ANALYSIS

Many computer runs were made to study the response of the helmeted head to selected inputs. Before the model of the canopy had been evolved, empirical data were available in terms of displacement of the canopy normal to its centerline as a function of applied force at the impact point. For the 1.6 cm thick canopy, the apparent stiffness was approximately 1.09×10^6 N/m. This value was used with the helmet test data to generate a force-displacement curve. Runs were made using this stiffness to determine the crewman's response in terms of injury criteria parameters.

The calculated outputs from the computer runs provide several interesting results. First, theoretical interference and computed crush or displacement do differ significantly at large input values of interference. Secondly, injury criteria values versus crush indicate that the differences do not significantly alter the interpretation of tolerability. That is, if a birdstrike results in a canopy deformation wave that would create 3.2 cm of interference, the resulting crush is nearly the same.

Tabulated results clearly show that any interference of greater than the least values computed, is excessive. There is little doubt that the kinematics of the head due to helmet crush depths of greater than 3.2 cm are intolerable. The question then becomes one of examining the responses at crush depths of nearly 2.5 cm.

For the two birdstrikes at 3 cm of interference, the acceleration waveforms were used as inputs to the MSC model to compute the longitudinal strain. This can be easily accomplished manually since the MSC model is a lightly damped (damping ratio of 0.028) system and the peak strain occurs in the first 3 milliseconds. The response of a lightly damped single degree of freedom system to a linear acceleration change is a relatively simple expression containing the period and natural frequency of the model as well as the acceleration rate and skull reference length. The waveforms examined were approximated by line segments and the strain of each segment was summed using superposition to calculate the maximum strain.

For the waveforms selected, the strain value is .003 cm/cm which is, according to the current criteria, tolerable, Examination of the greater crush depth waveforms makes it apparent that the other listed would greatly exceed the tolerable strain.

Other aspects of the birstrike phenomena that were examined using the model were the effects of the presence of a helmet visor and a headrest. Both were merely extensions of the developed model. For the visor, it was necessary to conduct laboratory experiments to measure the force displacement characteristics at many points. With this information, the stiffness at the impact point was then generated by combining the stiffness of the canopy, helmet and visor.

The longitudinal acceleration of the head as modified by the visor is seen in Figure 11. This is indicative of the response due to 3 cm interference with a stiff canopy. Although the presence of the visor has reduced the peak value of the acceleration, the calculated strain for both has the same magnitude. The increase in interference is apparently offset by the softness of the visor.

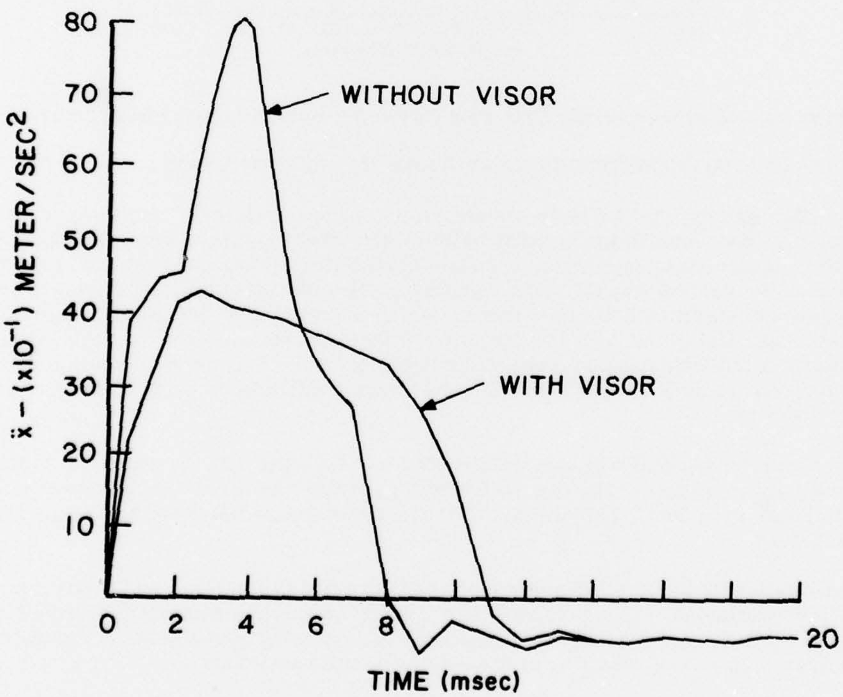

Figure 11. Head Acceleration Generated with and without Visor

The results that are presented are always related to original interference. This was done so that the applicability of the results would not be restricted. No effort was made to relate the interference to clearance within the F-16 canopy. This was done so that the results could be used to go first from injury to interference and then clearance. If an impact is tolerable, and the interference is 3 cm, then one can return to a cockpit drawing with selected percentiles of men at selected seat positions, and determine

what the acceptable clearance would be. For example, during a study of crew position for the F-16, crewmen head positions were established for analysis purposes for 5th, 50th and 95th percentile air-crewman seated at low, mid and upper seat position. The head positions were established by placing an anthropometric model in the seat and attempting to locate the crewman in the most comfortable position based upon head tilt and back support. With seat adjusted full up, the helmet position is such that an interference of 3 cm would require a deflection of about 4.6 cm for a 1.6 cm thick canopy. If another position were selected as being critical, the interference can be added to the helmet shell location and the depth of deflection established.

SUMMARY OF EFFORT

The purpose of the effort was to develop an analytical model of the birdstrike phenomena. As such, the model had to reflect the characteristics of the canopy, helmet, head and headrest as they influence one another. It was not sufficient to just have a model of each and subject them to selected impacts. The model had to reflect the interaction between all elements. Additionally, it was desired to be able to compare the kinetic outputs of the model with injury criteria parameters and have some means of overcoming the problem of acceleration waveform evaluation. The purpose of the effort was achieved in that the ATBM model in conjunction with the MSC model was used to simulate the total birdstrike process.

The ATBM model has the capability to reflect the kinetic process studied if adequate information is available. Specifically, test data are needed to establish the compliance, speed and direction of the canopy deflection. Also needed are force displacement measurements from the helmet impact tests and headrest tests. These, in conjunction with biomechanical data for the inertial, elastic and viscous characteristics of the human, can provide a realistic means of studying the overall system response from both a kinetic and injury potential viewpoint.

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